A New Structure for Comparing Surface Passivation Materials of GaAs Solar Cells *

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New Structure Design

The surface recombination velocity (S_{rec}) for bare GaAs is typically as high as 10^6 to 10^7 cm/sec, which dramatically lowers the efficiency of GaAs solar cells. Early attempts to circumvent this problem by making an ultra thin junction ($x_j < .1\ \mu$m) proved unsuccessful when compared to lowering S_{rec} by surface passivation [ref. 1,2,3]. Present day GaAs solar cells use an GaAlAs window layer to passivate the top surface [ref. 4,5]. The advantages of GaAlAs in surface passivation are its high bandgap energy and lattice matching to GaAs. Although GaAlAs is successful in reducing the surface recombination velocity, it has other inherent problems of chemical instability (Al readily oxidizes) and ohmic contact formation.

The search for new, more stable window layer materials requires a means to compare their surface passivation ability. Therefore, a device structure is needed to easily test the performance of different passivating candidates. Such a test device is shown in Figure 1.

This design has three important features:

1. The device allows direct comparison of identical GaAs solar cells with and without passivation. This is accomplished by growing the window layer on only half of the light active region and by employing a parallel metallization scheme. The solar cell can be cleaved in half, permitting any measurable improvements due to surface passivation to be related to the same GaAs solar cell without a window layer [Figure 2].

2. The structure avoids ohmic contact problems to the window layer. A separate thick p-GaAs region is grown to provide the necessary top contact [cf. Figure 1]. This thicker p-region prevents contact punch through of the thin p-GaAs collector, as well as blocking any shunt defects from forming due to incomplete window/collector layer growth. Since the objective is to compare the surface passivation ability of various materials, problems associated with making contacts to the window are eliminated.

3. The multilevel device provides for testing of all semiconductor layers of the solar cell (i.e., the absorber, collector, and window). Absorber contacts are formed on the exposed top portion of the n-GaAs layer, allowing measurement of the absorber layer's doping concentration and resistivity. The parallel contact pattern provides the same measurements of the p-GaAs collector. Further tests of the p/n junction solar cell supply numerous other useful parameters, as listed in Table 1.

The multilevel design is fabricated by utilizing the special masking abilities of the growth method used. The GaAs solar cell is grown by the liquid phase epitaxy (LPE) process using a horizontal sliding graphite boat. The LPE growth process is used because of its superior device performance [ref. 7]. Normal LPE grown layers have melt wells approximately equal in size to the seed and positioned linearly over the movable GaAs substrate. Pulling the seed wafer under each successive melt produces a multiple layer device, with each new layer completely covering the last one. This sliding boat technique allows for easy modification of melt sizes by opening wells of different areas at various locations over the seed position. Proper positioning of the GaAs substrate provides localized LPE (L^2PE) growth to occur only in designated regions on the seed wafer [Figure 3]. That is, the device is made by sequentially moving the substrate under each growth melt, forming localized layers on top of each other. This L^2PE process provides the freedom to design a multilevel structure to test surface passivation of GaAs solar cells.

Surface Recombination

Surface recombination in GaAs is due to excess anion charges at the crystal surface, which deforms the lattice. When GaAs is exposed to air (O_2), its surface forms a native oxide layer of about 20–50Å in thickness. This oxide is predominantly Ga_2O_3, although several forms of arsenic oxide can also form, namely As_2O_3 [ref. 8]. However, any As_2O_3 formed is unstable and reacts with GaAs at the GaAs–oxide interface to form elemental As through the chemical reaction [ref. 9]:

$$2GaAs + As_2O_3 \rightarrow Ga_2O_3 + 4As$$
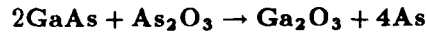
Thus, with much of the Ga on the surface bound together with oxygen, a large amount of elemental As is present at the interface. It is this free excess As anion concentration which causes a slight crystal deformation of GaAs at the surface [Figure 4a][ref. 10,11]. This rearrangement moves the empty energy states associated with the As atom from the conduction band into the bandgap region. These As acceptor states are located about .7 eV below the conduction band minimum ($\approx E_{gap}/2$), and are ideal recombination centers due to their mid bandgap energy level [Figure 4b][ref. 11].

Surface recombination in GaAs solar cells deteriorates the light generated current (J_{light}), as minority carriers are trapped by the recombination centers of the surface As atoms, instead of being collected at the junction. However, surface recombination also detrimentally affects (i.e., increases) the reverse saturation current (J_o). The combined effect of these two increased losses are shown in the open circuit voltage (V_{oc}) of the solar cell. That is, a reduction in surface recombination (S_{rec}) will result in higher open circuit voltages. Thus, a change in V_{oc} as measured by this new structure indicates the level of surface passivation by any material.

Solar Cell Equation:

$$J = J_o(e^{qV/kT} - 1) - J_{light}$$

$$V_{oc} = \frac{kT}{q} \ln\left(\frac{J_{light}}{J_o}\right)$$

Surface Passivation

The window layer passivates the surface of the GaAs solar cells by eliminating dangling bonds and reducing the surface recombination velocity (S_{rec}). Theoretical calculations predict passivated, high efficiency GaAs solar cells when S_{rec} is reduced from its normally high $10^6 - 10^7$ cm/sec to only 10^4 cm/sec [Figure 6]. In essence, the window material does not need to achieve perfect surface passivation ($S_{rec} \rightarrow 0$) in order to obtain optimum performance from GaAs, only a lowering of S_{rec} to 10^4 cm/sec is required.

Numerous materials are available for trial application to GaAs, but choice of the best window layer should meet most of the criteria described below:

Surface Passivation Material Design Rules for GaAs

1. Passivate the top surface of GaAs by reducing S_{rec} to $10^3 - 10^4$ cm/sec.

2. Be transparent to the useful sunlight of GaAs (i.e., $E_{gap}^{window} > E_{gap}^{GaAs}$).

3. Chemically stable in space and earth atmosphere for the duration of the solar cell's life.

4. Minimize lattice mismatch to GaAs.

5. Form stable, low resistance ohmic contacts.

Some promising window candidates are given in Table 2. New semiconductor compounds incorporating Al are still applicable (i.e., $Al_{.48}In_{.52}P$), since Al_x mole fractions of $x \leq .50$ may be stable and form ohmic contacts [ref. 12].

New window layer materials must reduce S_{rec} by tying up the excess As anions at the surface, or by preventing atomic As from forming. The first procedure involves a chemical reaction which bonds the As with the passivating material (e.g., $Na_2S \cdot 9H_2O$ [ref. 13]), while the latter procedure requires the application of a window layer on the freshly grown GaAs before oxidation occurs (e.g., GaAlAs or GaP). Finally, a combination of these procedures could be used to allow a broader range of window layer materials. An example of this might be the application of $Na_2S \cdot 9H_2O$ on the GaAs surface, followed immediately by the application of a layer preventing surface oxidation. Using the new device structure will provide accurate comparisons of various experimental window materials now under investigation.

References

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Table 1

| Available Non-Destructive Tests for the Multilevel Structure	
Test Station	Calculated Parameters
Current – Voltage (IV)	$I_{sc}, V_{oc}, P_{max}, \eta, FF$ $I_0, A, R_{shunt}, R_{series}$
Four Point Probe	$\rho_{collector}, \rho_{absorber}$ N_A, N_D, μ_n $R_{contacts}$ [6]
Capacitance – Voltage (CV)	N_D
Spectral Response	η_q, L_n, S_{rec}

Table 2

| Prospective Window Layer Materials for GaAs Solar Cells				
Semiconductor Material	E_{gap} (eV)	Bandgap Type	Lattice Constant (Å)	Lattice Mismatch (%)
GaAs	1.424	direct	5.653	—
Ga$_{.15}$Al$_{.85}$As	2.103	indirect	5.659	0.106
GaP	2.260	indirect	5.451	3.573
GaAs$_{.50}$P$_{.50}$	2.043	indirect	5.552	1.787
Ga$_{.51}$In$_{.49}$P	1.883	direct	5.653	—
Al$_{.48}$In$_{.52}$P	2.350	indirect	5.653	—
ZnSe	2.670	direct	5.667	0.248
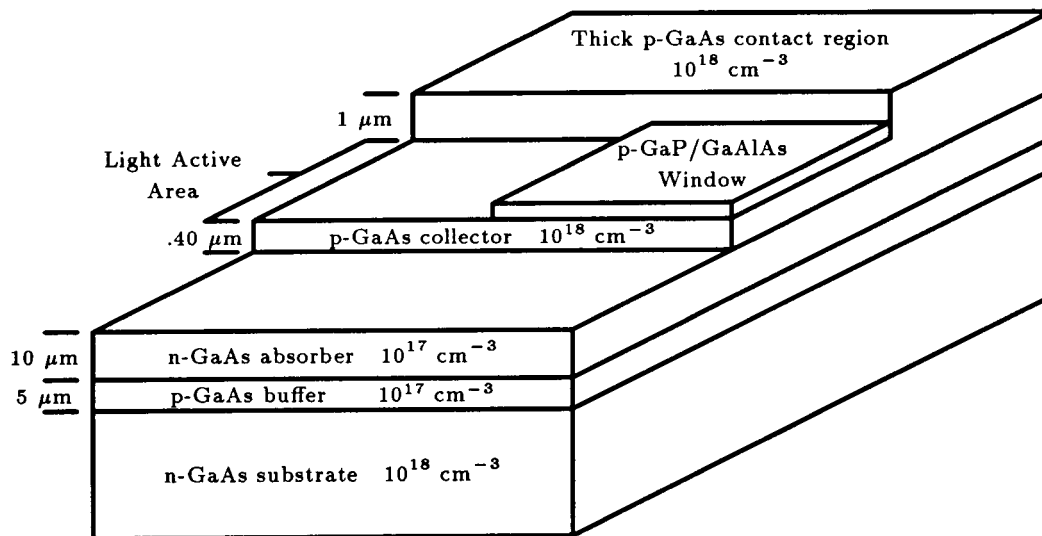
**Figure 1.** Multilevel structure side view showing the grown layers.
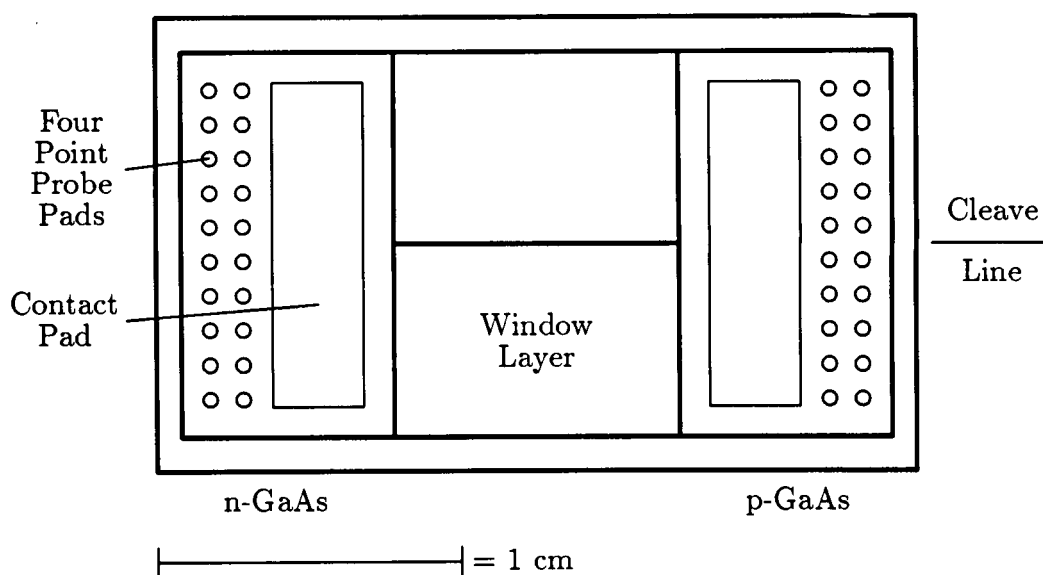
Figure 2. Top view of test structure showing metallization pattern.
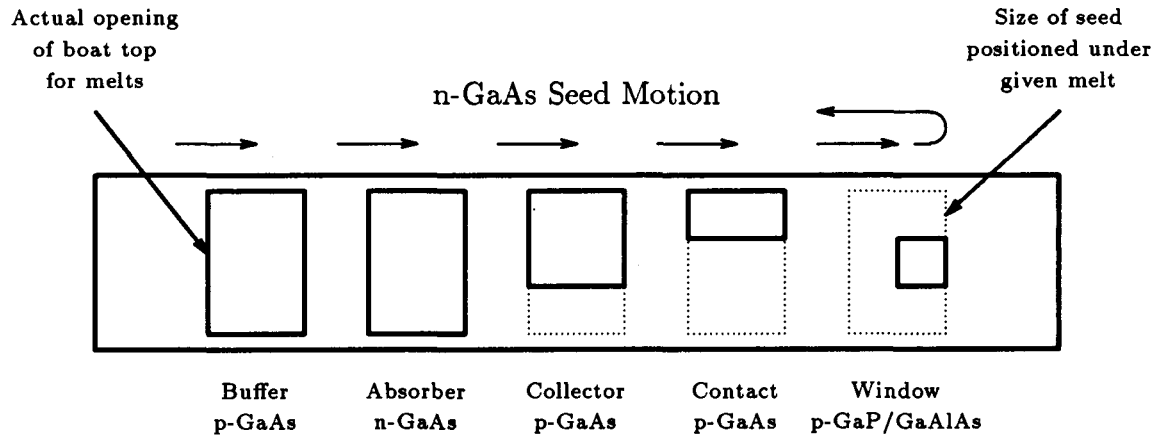
Figure 3. General schematic of L²PE melt positions to grow the test device structure.
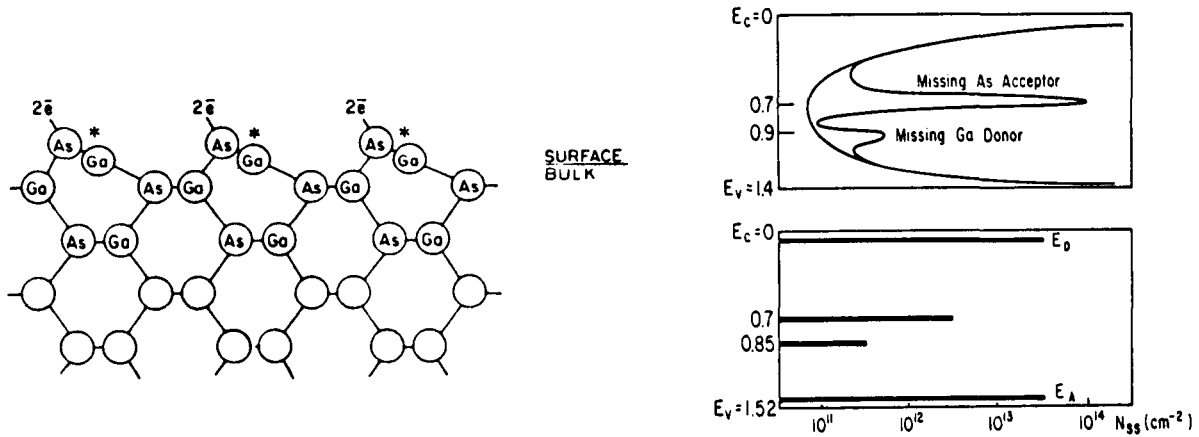
Figure 4. (a) Schematic of GaAs lattice structure at the surface due to presence of excess As atoms [10], and (b) the corresponding shift of interface state density distributions inside the energy bandgap region [11].
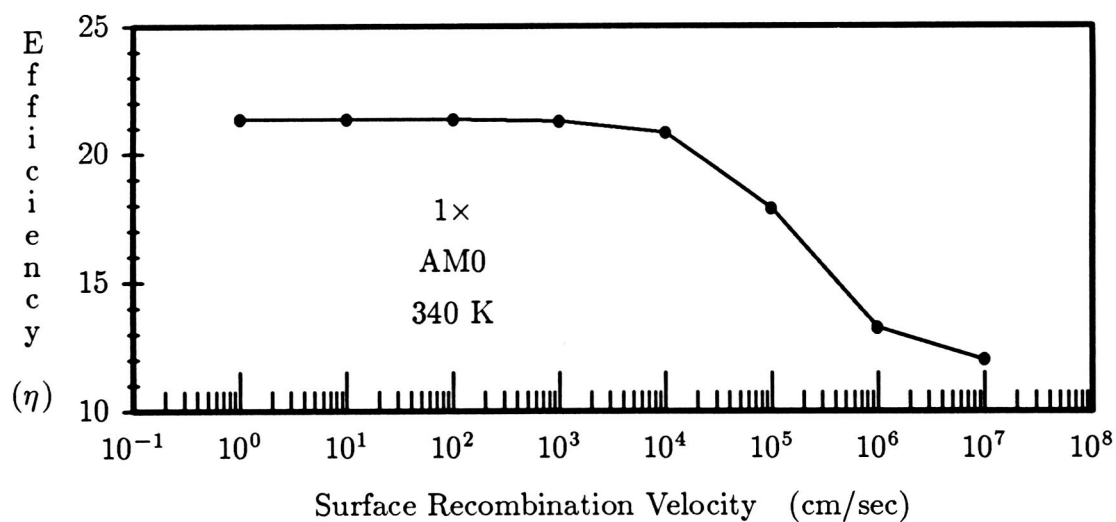
Figure 5. Theoretical calculation of output power efficiency vs. surface recombination velocity for an N/P GaAs solar cell (with losses).
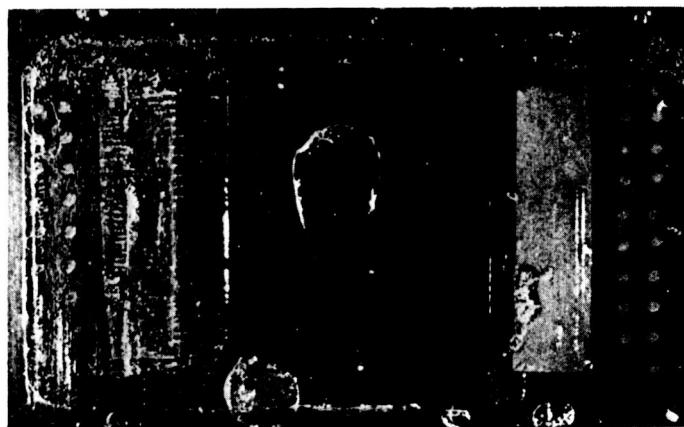
Figure 6. Top view photograph showing preliminary L²PE growth process of multilevel GaAs solar cell with GaAlAs window layer.